

# Rare $\tau$ Decays in R-parity Violating Supersymmetry

Roshni Bose

Department of Physics, University of Calcutta,  
92, Acharya Prafulla Chandra Road, Kolkata 700 009, India

## Abstract

We constrain, from rare  $\tau$  decays, several combinations of  $\lambda$  and  $\lambda'$  type couplings coming from Supersymmetry without R-parity. The processes that we consider are  $\tau \rightarrow \ell M$ ,  $\tau \rightarrow \ell_i \ell_j \ell_k$ , and  $\tau \rightarrow \ell \gamma$ , where  $\ell$  stands for either  $e$  or  $\mu$ , and  $M$  is the generic symbol for a meson. We update several existing bounds, and provide a few new ones too.

PACS numbers: 12.60.Jv, 13.35.Dx

December 9, 2010

# 1 Introduction

The hope to discover physics beyond the Standard Model (SM), which we might call New Physics (NP) for simplicity, is the principal *raison d'être* for particle physicists. There are several motivations, and there are innumerable candidates, but Supersymmetry, in its various avatars, stand out. As it appears, lepton and baryon numbers, L and B respectively, are good symmetries of the minimal Supersymmetric SM, but they are accidental symmetries in the sense that L and B violating interactions are not *a priori* forbidden in the superpotential, and one has to impose this *ad hoc* for B and L violating couplings to be zero at every energy scale. What one does is to consider a discrete symmetry, called R-parity, defined as

$$R_p = (-1)^{3B+L+2S}, \quad (1)$$

where S is the spin of the particle. By definition,  $R_p = +1$  for particles and  $R_p = -1$  for superparticles, and  $R_p$  is imposed as a good symmetry of the superpotential. This forbids B and L violating interactions separately, and makes the lightest supersymmetric particle (LSP) stable and a good candidate for the dark matter. On the other hand, if  $R_p$  is not a good symmetry, the signatures change drastically, because all superparticles, including the LSP, can decay inside the detector.

There can be 45  $R_p$ -violating (RPV) couplings in the superpotential coming from the renormalizable terms

$$W_{R_p} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c, \quad (2)$$

where  $L$ ,  $Q$ ,  $E$ ,  $U$  and  $D$  stand for lepton doublet, quark doublet, lepton singlet, up-type quark singlet, and down-type quark singlet superfields respectively;  $i, j, k$  are generation indices that can run from 1 to 3; and  $\lambda_{ijk}$  ( $\lambda''_{ijk}$ ) are antisymmetric in  $i$  and  $j$  ( $j$  and  $k$ ). The phenomenology of RPV supersymmetry, including the collider signatures and bounds on these couplings, may be found in [1].

In this work we would like to constrain several L-violating coupling combinations from rare  $\tau$  decays. The decays that we will consider are  $\tau \rightarrow \ell M$ ,  $\tau \rightarrow \ell_i \ell_j \ell_k$ , and  $\tau \rightarrow \ell \gamma$ , where  $\ell$  stands for  $e$  or  $\mu$ ,  $M$  for any generic meson, and  $i, j, k$  are generation indices that can be 1 or 2. These decays being L violating, we will consider only  $\lambda$  and  $\lambda'$  type couplings, as simultaneous L and B violation would lead to an unacceptably fast proton decay. There are some such studies in the literature [2, 3, 4] whose bounds we will update. We will also give a number of new bounds coming from radiative  $\tau$  decays. However, as we will see, most of the

combinations are also bound from leptonic and semileptonic lepton flavour violating (LFV) decays, and those numbers are better by more than an order of magnitude.

The paper is organized as follows. In Section II, we compile the relevant expressions. Section III deals with the analysis and the bounds that we obtain. Section IV is on the possible implications of these bounds on the ongoing experiments. We summarize and conclude in Section V.

## 2 Relevant Expressions

We work in the framework of an explicit RPV model, with a hierarchical scheme of couplings: only those couplings that are relevant will be assumed to dominate the others. For all decays that we will be interested in, we need two different couplings, of the form  $\lambda\lambda$ ,  $\lambda\lambda'$ , or  $\lambda'\lambda'$ . We assume the hierarchical structure at the weak scale, and do not investigate the possible high-scale theory behind them. Also, at the weak scale, we assume these terms to appear in the mass basis of the quarks, and not in the flavour basis, so that there is no further constraints on other couplings coming from a Cabibbo-Kobayashi-Maskawa (CKM) type rotation. We also assume the bilinear couplings of the generic form  $-\mu_i L_i H_2$ , where  $H_2$  is the superfield that gives mass to charged leptons and down-type quarks, to be zero at the weak scale. This also relaxes the possible constraints coming from the neutrino masses and mixing angles in presence of the bilinear terms. However, even some trilinear combinations like  $\lambda_{ikl}^{(\prime)} \lambda_{jlk}^{(\prime)}$  can generate nonzero entries for the  $ij$ -th element of the neutrino mass  $\mathcal{M}_\nu$  [1].

For the decays  $\tau \rightarrow \ell M$  or  $\tau \rightarrow 3\ell$ , the relevant four-fermion operator, which one may get by integrating the sfermion field out in eq. (2). The expression reads [3, 4]

$$\begin{aligned} \mathcal{H}_{R\ell} = & L_{jklm} (\bar{\ell}_l (1 + \gamma_5) \ell_m) (\bar{\ell}_k (1 - \gamma_5) \ell_j) \\ & + A_{jklm} (\bar{\ell}_j (1 - \gamma_5) \ell_k) (\bar{d}_m (1 + \gamma_5) d_l) \\ & - \frac{1}{2} B_{jklm} (\bar{\ell}_j \gamma^\mu (1 - \gamma_5) \ell_l) (\bar{d}_m \gamma_\mu (1 + \gamma_5) d_k) \\ & + \frac{1}{2} C_{jklm} (\bar{\ell}_j \gamma^\mu (1 - \gamma_5) \ell_l) (\bar{u}_k \gamma_\mu (1 - \gamma_5) u_m) + \text{H.c.}, \end{aligned} \quad (3)$$

where

$$\begin{aligned} L_{jklm} &= \sum_{i=1}^3 \frac{\lambda_{ijk} \lambda_{ilm}^*}{4M_{\tilde{\nu}_{iL}}^2}, \quad A_{jklm} = \sum_{i=1}^3 \frac{\lambda_{ijk}^* \lambda'_{ilm}}{4M_{\tilde{\nu}_{iL}}^2}, \\ B_{jklm} &= \sum_{i=1}^3 \frac{\lambda'_{lim} \lambda_{jik}^*}{4M_{\tilde{u}_{iL}}^2}, \quad C_{jklm} = \sum_{i=1}^3 \frac{\lambda'_{lmi} \lambda_{jki}^*}{4M_{\tilde{d}_{iR}}^2}. \end{aligned} \quad (4)$$

We take, as a benchmark value, all sfermions to be degenerate at 100 GeV. While this value is experimentally not favoured any more, the bounds scale with  $M_{\tilde{f}}^2$ , as is evident from eqs. (3) and (4), and it is easier to compare with earlier results available in the literature.

If the final state consists of three leptons, only the  $L$  term is important. For a final state with a meson consisting of two down-type quarks, both  $A$  and  $B$  terms contribute. If the meson consists of up-type quarks only, the  $C$  term is relevant. For mesons like  $\pi^0$ ,  $\eta$ , or  $\eta'$  in the final state, all terms  $A, B, C$  are important. Anyway, we will consider only one of them to be nonzero at a time, so we do not entertain any possibility of interference. There is, of course, no SM contributions to these processes.

We do not consider the running of the RPV couplings between the sfermion scale and the low-energy scale. The corrections, for a hierarchical scheme, consists of a scaling by a factor between 2 and 3 [5], and hence can be dumped into the low-energy value of these couplings. The only QCD correction may occur between two quark fields; for  $\tau$  decays, the pair hadronizes, absorbing all the uncertainty in the decay constant.

For mesonic decays of the  $\tau$ , the nonzero  $\lambda\lambda'$  type couplings can only result in a pseudoscalar meson in the final state; that a vector meson is forbidden is evident from the Lorentz structure of the  $B$  and  $C$  type operators. The decay width for a final state pseudoscalar meson  $P$  with quark content  $\bar{q}_j q_k$ , mass  $M_P$ , and decay constant  $f_P$ , can be written as

$$\Gamma(\tau \rightarrow P \ell_i) = \frac{(M_\tau^2 + M_{\ell_i}^2 - M_P^2)C(M_\tau^2, M_{\ell_i}^2, M_P^2)f_P^2 M_P^4}{128\pi M_\tau^3 M_\nu^4 (M_{q_j} + M_{q_k})^2} |\lambda_{ni3}^* \lambda'_{nj3}|^2, \quad (5)$$

where

$$C(x, y, z) = \sqrt{x^2 + y^2 + z^2 - 2xy - 2yz - 2zx}. \quad (6)$$

The above expression has to be multiplied by  $\frac{1}{2}$  if there is a  $\pi^0$  in the final state. Note that the combination  $|\lambda_{n3i}^* \lambda'_{nkj}|$  can also be bounded from the same decays, with identical expressions.

The generic couplings  $B$  and  $C$  mediate the decay  $\tau \rightarrow \ell_i + M$  where  $M$  is any pseudoscalar or vector meson, with quark content  $\bar{q}_j q_k$ , and decay constant  $f_M$ . The decay widths are given by

$$\Gamma(\tau \rightarrow \ell_i + M) = \frac{f_M^2 C(M_\tau, M_{\ell_i}, M_M) F_0(M_\tau, M_{\ell_i}, M_M)}{512\pi \tilde{M}^4 M_\tau^3} |\lambda'_{3nk} \lambda_{inj}^*|^2, \quad (7)$$

where the  $C$ -function is given in eq. (6),  $\tilde{M}$  is the mass of the mediating sfermion, and

$$\begin{aligned} \text{Pseudoscalar} & : F_0(x, y, z) = (x^2 - y^2)^2 - z^2(x^2 + y^2), \\ \text{Vector} & : F_0(x, y, z) = z^2(x^2 + y^2 - z^2) + (x^2 - y^2)^2 - z^4. \end{aligned} \quad (8)$$

For the radiative decays, the invariant amplitude for  $\tau \rightarrow \ell_i + \gamma$  can be written as [2]

$$\begin{aligned}\mathcal{M} &= i\bar{u}_\ell(k)T(1 + \gamma_5)\sigma_{\mu\nu}q^\nu u_\tau(p)\epsilon^\mu(q), \\ &= T\bar{u}_\ell(k)(1 + \gamma_5)(2\epsilon \cdot p - M_\tau \not{\epsilon})u_\tau(p),\end{aligned}\tag{9}$$

where  $p$ ,  $k$ , and  $q = p - k$  are the momenta of the  $\tau$ , the daughter lepton, and the photon respectively.  $\epsilon^\mu(q)$  is the polarization vector for the photon, and  $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$ . To get the last line of the Gordon decomposition, we have neglected the final state lepton mass. For  $\lambda$ -type couplings,

$$T = \frac{ie\lambda_1\lambda_2 M_\tau}{16\pi^2 \tilde{M}^2} F(x),\tag{10}$$

with

$$F(x) = \frac{N_c}{24(x-1)^3} \left[ \left( 2x^2 + 5x - 1 - \frac{6x^2 \ln x}{x-1} \right) - \left( x^2 - 5x - 2 + \frac{6x \ln x}{x-1} \right) \right],\tag{11}$$

where  $x$  is the ratio of fermion and sfermion masses squared:  $x = M_f^2/\tilde{M}^2$ . For  $\lambda$ -type couplings, they are leptons and sleptons, and  $N_c = 1$ . For  $\lambda'$ -type couplings, they are quarks and squarks, and  $N_c = 3$ . One can neglect all fermion masses compared with the sfermions, except for the top quark, and in the limit  $x \rightarrow 0$ ,  $F(x) \rightarrow -N_c/24$ . The expression is simplified from the fact that (s)neutrinos do not couple to the photon. For  $\lambda'$ -type couplings, both up- and down-type (s)quarks may couple to the photon, and the corresponding expression is more complicated [2]:

$$T = \frac{ie\lambda'_1\lambda'_2 M_\tau}{16\pi^2 \tilde{M}^2} \left[ F_1\left(\frac{M_d^2}{\tilde{M}^2}\right) + F_2\left(\frac{M_u^2}{\tilde{M}^2}\right) \right],\tag{12}$$

where

$$\begin{aligned}F_1(x) &= \frac{N_c}{24(x-1)^3} \left[ \frac{2}{3} \left( 2x^2 + 5x - 1 - \frac{6x^2 \ln x}{x-1} \right) - \frac{1}{3} \left( x^2 - 5x - 2 + \frac{6x \ln x}{x-1} \right) \right], \\ F_2(x) &= \frac{N_c}{24(x-1)^3} \left[ \frac{1}{3} \left( 2x^2 + 5x - 1 - \frac{6x^2 \ln x}{x-1} \right) - \frac{2}{3} \left( x^2 - 5x - 2 + \frac{6x \ln x}{x-1} \right) \right],\end{aligned}\tag{13}$$

with  $M_u$  and  $M_d$  standing for the masses of generic up- or down-type quarks respectively.

This form of  $T$  is easy to understand. A helicity flip between incoming  $\tau$  and outgoing lepton is needed, so both the tensor and the pseudotensor amplitudes in eq. (9) will be proportional to  $M_\tau$  (assuming that  $M_e$  and  $M_\mu$  can be neglected). They will also be proportional to the product of two RPV couplings, and the electric charge  $Q$  of the particle coupling to the photon. There will be a further factor of  $1/16\pi^2$  coming from the loop, and  $1/\tilde{M}^2$  from the sparticle propagator. We refer the reader to [2] for the relevant Feynman diagrams.

The decay width can be written as

$$\Gamma(\tau \rightarrow \ell_i + \gamma) = \frac{M_\tau^3}{4\pi} |T|^2, \quad (14)$$

and the branching ratio is

$$\text{BR}(\tau \rightarrow \ell_i \gamma) = \frac{48\pi^2}{G_F^2 M_\tau^2} |T|^2. \quad (15)$$

Mode	BR (upper limit) ( $\times 10^8$ )	Mode	BR (upper limit) ( $\times 10^8$ )
$e\gamma$	3.3	$\mu\gamma$	4.4
$e\pi^0$	2.2	$\mu\pi^0$	2.7
$e\eta$	4.4	$\mu\eta$	2.3
$e\eta'$	3.6	$\mu\eta'$	3.8
$eK_S$	2.6	$\mu K_S$	2.3
$e\rho^0$	1.8	$\mu\rho^0$	1.2
$e\phi$	3.1	$\mu\phi$	8.4
$e\omega$	4.8	$\mu\omega$	4.7
$eK^{*0}$	3.2	$\mu K^{*0}$	7.2
$e\overline{K}^{*0}$	3.4	$\mu\overline{K}^{*0}$	7.0
$e^-e^+e^-$	2.7	$\mu^-\mu^+\mu^-$	2.1
$e^-e^+\mu^-$	1.8	$\mu^-\mu^+e^-$	2.7
$e^-e^-\mu^+$	1.5	$\mu^-\mu^-e^+$	1.7

Table 1: Upper limits of various lepton-flavor violating  $\tau$  decays. The numbers are taken from: [6] (radiative), [7] (lepton + pseudoscalar), [8] (lepton + vector), [9] (trilepton).

The upper bounds at 90% confidence limit (CL) on the branching ratios of several lepton-flavor violating (LFV)  $\tau$  decay channels are shown in Table 1. The quoted numbers are for integrated luminosities of  $470 \text{ fb}^{-1}$  at  $\Upsilon(4S)$  plus  $46 \text{ fb}^{-1}$  at  $\Upsilon(3S)$  and  $\Upsilon(2S)$  (SLAC, radiative decays),  $802 \text{ fb}^{-1}$  at  $\Upsilon(4S)$  and  $99 \text{ fb}^{-1}$  at  $\Upsilon(5S)$  (KEK-B, lepton plus a pseudoscalar meson),  $782 \text{ fb}^{-1}$  at  $\Upsilon(4S)$  and  $72 \text{ fb}^{-1}$  at  $\Upsilon(5S)$  (KEK-B, lepton plus a vector meson), and  $782 \text{ fb}^{-1}$  at  $\Upsilon(4S)$  (KEK-B, trilepton). It is useful to note that apart from very few numbers coming from radiative decays with top quark in the loop, the bounds on the product couplings are given by

$$\text{Actual bound} = \text{Bound quoted} \times \left( \frac{\tilde{M}}{100} \right)^2 \times \left( \frac{\text{Actual BR bound}}{\text{Quoted BR bound}} \right)^{1/2}, \quad (16)$$

where the quoted bounds on branching ratios are those to be found in Table 1 while the actual bounds are the possibly improved numbers as can be obtained from LHC-B or Super B factories.

### 3 Results

Our results are shown in Tables 2-5. Table 2 shows the bounds on  $|\lambda_{ijk}\lambda_{ilm}|$  as obtained from the lepton flavour violating trileptonic  $\tau$  decays, see eqs. (3) and (4), taking into account the fact that  $\lambda_{ijk}$  is antisymmetric in  $i$  and  $j$ . The last column in each of the Tables 2-4 is taken from [4].

Tables 3 and 4 show the bounds on  $\lambda\lambda'$  and  $\lambda'\lambda'$  type products (again, magnitudes only, as all these processes are SM-forbidden and hence single-amplitude processes) coming from  $\tau$  decays to a charged lepton and a neutral meson.

Neutrino masses put the tightest constraint on some of the RPV couplings. A typical bound from the diagonal entries of the neutrino mass matrix  $\mathcal{M}_\nu$  is [10]

$$|\lambda'_{i11}| < 6.0 \times 10^{-3}, \quad |\lambda'_{i22}| < 3.5 \times 10^{-5}, \quad |\lambda'_{i33}| < 8.9 \times 10^{-6}. \quad (17)$$

Assuming all sleptons to be degenerate (and all squarks too), and the trilinear  $A$ -terms to be proportional to the corresponding Yukawa couplings, the lepton-slepton and quark-squark loops contribute to the neutrino mass matrix, even in the absence of any bilinear RPV interaction:

$$\begin{aligned} [\mathcal{M}_\nu]_{ij} &\approx \frac{1}{8\pi^2 \tilde{M}_e^2} (A^e - \mu \tan \beta) \sum_{k,l} \lambda_{ikl} \lambda_{jlk} M_{e_k} M_{e_l}, \\ [\mathcal{M}_\nu]_{ij} &\approx \frac{3}{8\pi^2 \tilde{M}_d^2} (A^d - \mu \tan \beta) \sum_{k,l} \lambda'_{ikl} \lambda'_{jlk} M_{d_k} M_{d_l}. \end{aligned} \quad (18)$$

The combinations that affect eq. (18) are shown with superscripts  $\nu ij$  in the respective tables.

A total of 12  $\lambda\lambda$  combinations are bound from the radiative decays  $\tau \rightarrow e + \gamma$  and  $\tau \rightarrow \mu + \gamma$ . Among them, ten have been shown in Table 2; they are definitely less severe than those coming from trilepton decays. We also have

$$|\lambda_{123}\lambda_{233}| < 1.2 \times 10^{-2} \quad (e + \gamma), \quad |\lambda_{123}\lambda_{133}| < 1.4 \times 10^{-2} \quad (\mu + \gamma). \quad (19)$$

Table 5 shows the bounds on  $\lambda'\lambda'$  type products coming from radiative decays  $\tau \rightarrow \mu\gamma$  and  $\tau \rightarrow e\gamma$ . Apart from the combinations  $\lambda'_{i23}\lambda'_{323}$  and  $\lambda'_{i33}\lambda'_{333}$  ( $i, j = 1, 2$ ), all other combinations have a better bound as shown in Table 4.

$\lambda\lambda$	Process	Our bound	Previous bound
(121)(123) $e\gamma$	$\tau \rightarrow ee\bar{e}$	$1.8 \times 10^{-4}$	$7.0 \times 10^{-4}$
(121)(123) $^\dagger$	$\tau \rightarrow e\mu\bar{\mu}$	$2.6 \times 10^{-4}$	$7.0 \times 10^{-4}$
(121)(131) $\nu^{23,\mu\gamma}$	$\tau \rightarrow \mu e\bar{e}$	$2.1 \times 10^{-4}$	$6.8 \times 10^{-4}$
(121)(132) $\nu^{13}$	$\tau \rightarrow \mu\mu\bar{e}$	$1.4 \times 10^{-4}$	$5.6 \times 10^{-4}$
(121)(231) $e\gamma$	$\tau \rightarrow ee\bar{e}$	$1.8 \times 10^{-4}$	$7.0 \times 10^{-4}$
(121)(232)	$\tau \rightarrow \mu e\bar{e}$	$2.1 \times 10^{-4}$	$6.8 \times 10^{-4}$
(122)(123) $\mu\gamma$	$\tau \rightarrow \mu\mu\bar{\mu}$	$1.6 \times 10^{-4}$	$6.8 \times 10^{-4}$
(122)(123) $^\dagger$	$\tau \rightarrow \mu e\bar{e}$	$2.1 \times 10^{-4}$	$6.8 \times 10^{-4}$
(122)(131)	$\tau \rightarrow e\mu\bar{\mu}$	$2.6 \times 10^{-4}$	$7.0 \times 10^{-4}$
(122)(132) $\mu\gamma$	$\tau \rightarrow \mu\mu\bar{\mu}$	$1.6 \times 10^{-4}$	$6.8 \times 10^{-4}$
(122)(231)	$\tau \rightarrow ee\bar{\mu}$	$1.4 \times 10^{-4}$	$5.2 \times 10^{-4}$
(122)(232) $\nu^{13,e\gamma}$	$\tau \rightarrow e\mu\bar{\mu}$	$2.6 \times 10^{-4}$	$7.0 \times 10^{-4}$
(131)(133) $\nu^{13,e\gamma}$	$\tau \rightarrow ee\bar{e}$	$1.8 \times 10^{-4}$	$7.0 \times 10^{-4}$
(131)(233)	$\tau \rightarrow \mu e\bar{e}$	$2.1 \times 10^{-4}$	$6.8 \times 10^{-4}$
(132)(133) $\mu\gamma$	$\tau \rightarrow \mu e\bar{e}$	$2.1 \times 10^{-4}$	$6.8 \times 10^{-4}$
(132)(233) $\nu^{13}$	$\tau \rightarrow \mu\mu\bar{e}$	$1.4 \times 10^{-4}$	$5.6 \times 10^{-4}$
(133)(231) $\nu^{23}$	$\tau \rightarrow ee\bar{\mu}$	$1.4 \times 10^{-4}$	$5.2 \times 10^{-4}$
(133)(232)	$\tau \rightarrow e\mu\bar{\mu}$	$2.6 \times 10^{-4}$	$7.0 \times 10^{-4}$
(231)(233) $e\gamma$	$\tau \rightarrow e\mu\bar{\mu}$	$2.6 \times 10^{-4}$	$7.0 \times 10^{-4}$
(232)(233) $\nu^{23,\mu\gamma}$	$\tau \rightarrow \mu\mu\bar{\mu}$	$1.6 \times 10^{-4}$	$6.8 \times 10^{-4}$

Table 2: Bounds on  $\lambda_{ijk}\lambda_{pqr}$  from  $\tau \rightarrow \ell_i\ell_j\ell_k$  decays. All sleptons are assumed to be degenerate at 100 GeV, see eq. (16). The superscript  $\nu ij$  indicates that the combination generates the  $ij$ -th entry of the neutrino mass matrix  $\mathcal{M}_\nu$ ; for more details, see text. The couplings marked with  $e\gamma$  have a less severe upper bound of  $1.2 \times 10^{-2}$  coming from  $\tau \rightarrow e + \gamma$ ; similarly, those marked with  $\mu\gamma$  have an upper bound of  $1.4 \times 10^{-2}$  from  $\tau \rightarrow \mu + \gamma$ . The bounds marked with a dagger are not the best bounds right now, but we keep them as they are of comparable order.



$\lambda\lambda'$	Process	Our bound	Previous bound
(123)(111)	$\tau \rightarrow \mu\eta$	$3.2 \times 10^{-5}$	$6.7 \times 10^{-5}$
(123)(112)	$\tau \rightarrow \mu K_S$	$1.4 \times 10^{-4}$	$1.0 \times 10^{-3}$
(123)(121)	$\tau \rightarrow \mu K_S$	$1.4 \times 10^{-4}$	$1.0 \times 10^{-3}$
(123)(122)	$\tau \rightarrow \mu\eta$	$3.1 \times 10^{-4}$	$3.7 \times 10^{-4}$
(123)(211)	$\tau \rightarrow e\eta$	$4.5 \times 10^{-5}$	$8.5 \times 10^{-5}$
(123)(212)	$\tau \rightarrow e K_S$	$1.5 \times 10^{-4}$	$9.7 \times 10^{-4}$
(123)(221)	$\tau \rightarrow e K_S$	$1.5 \times 10^{-4}$	$9.7 \times 10^{-4}$
(123)(222)	$\tau \rightarrow e\eta$	$4.3 \times 10^{-4}$	$4.6 \times 10^{-4}$
(131)(111)	$\tau \rightarrow e\eta$	$4.5 \times 10^{-5}$	$8.5 \times 10^{-5}$
(131)(112)	$\tau \rightarrow e K_S$	$1.5 \times 10^{-4}$	$9.7 \times 10^{-4}$
(131)(121)	$\tau \rightarrow e K_S$	$1.5 \times 10^{-4}$	$9.7 \times 10^{-4}$
(131)(122)	$\tau \rightarrow e\eta$	$4.3 \times 10^{-4}$	$4.6 \times 10^{-4}$
(132)(111)	$\tau \rightarrow \mu\eta$	$3.2 \times 10^{-5}$	$6.7 \times 10^{-5}$
(132)(112)	$\tau \rightarrow \mu K_S$	$1.4 \times 10^{-4}$	$1.0 \times 10^{-3}$
(132)(121)	$\tau \rightarrow \mu K_S$	$1.4 \times 10^{-4}$	$1.0 \times 10^{-3}$
(132)(122)	$\tau \rightarrow \mu\eta$	$3.1 \times 10^{-4}$	$3.7 \times 10^{-4}$
(133)(311)	$\tau \rightarrow e\eta$	$4.5 \times 10^{-5}$	$8.5 \times 10^{-5}$
(133)(312)	$\tau \rightarrow e K_S$	$1.5 \times 10^{-4}$	$9.7 \times 10^{-4}$
(133)(321)	$\tau \rightarrow e K_S$	$1.5 \times 10^{-4}$	$9.7 \times 10^{-4}$
(133)(322)	$\tau \rightarrow e\eta$	$4.3 \times 10^{-4}$	$4.6 \times 10^{-4}$
(231)(211)	$\tau \rightarrow e\eta$	$4.5 \times 10^{-5}$	$8.5 \times 10^{-5}$
(231)(212)	$\tau \rightarrow e K_S$	$1.5 \times 10^{-4}$	$9.7 \times 10^{-4}$
(231)(221)	$\tau \rightarrow e K_S$	$1.5 \times 10^{-4}$	$9.7 \times 10^{-4}$
(231)(222)	$\tau \rightarrow e\eta$	$4.3 \times 10^{-4}$	$4.6 \times 10^{-4}$
(232)(211)	$\tau \rightarrow \mu\eta$	$3.2 \times 10^{-5}$	$6.7 \times 10^{-5}$
(232)(212)	$\tau \rightarrow \mu K_S$	$1.4 \times 10^{-4}$	$1.0 \times 10^{-3}$
(232)(221)	$\tau \rightarrow \mu K_S$	$1.4 \times 10^{-4}$	$1.0 \times 10^{-3}$
(232)(222)	$\tau \rightarrow \mu\eta$	$3.1 \times 10^{-4}$	$3.7 \times 10^{-4}$
(233)(311)	$\tau \rightarrow \mu\eta$	$3.2 \times 10^{-5}$	$6.7 \times 10^{-5}$
(233)(312)	$\tau \rightarrow \mu K_S$	$1.4 \times 10^{-4}$	$1.0 \times 10^{-3}$
(233)(321)	$\tau \rightarrow \mu K_S$	$1.4 \times 10^{-4}$	$1.0 \times 10^{-3}$
(233)(322)	$\tau \rightarrow \mu\eta$	$3.1 \times 10^{-4}$	$3.7 \times 10^{-4}$

Table 3: Bounds on  $\lambda_{ijk}\lambda'_{pqr}$  from  $\tau \rightarrow \ell + M$  decays, where  $M$  is a pseudoscalar meson. Again, all sleptons are assumed degenerate at 100 GeV.

$\lambda'\lambda'$	Process	Our bound	Previous bound
(111)(311) $\nu^{11}$	$\tau \rightarrow e\rho$	$2.3 \times 10^{-4}$	$2.4 \times 10^{-3}$
(111)(312)	$\tau \rightarrow e\overline{K^{0*}}$	$2.9 \times 10^{-4}$	$3.6 \times 10^{-3}$
(112)(311)	$\tau \rightarrow eK^{0*}$	$2.8 \times 10^{-4}$	$2.9 \times 10^{-3}$
(112)(312)	$\tau \rightarrow e\phi$	$2.3 \times 10^{-4}$	$3.4 \times 10^{-3}$
(113)(313)	$\tau \rightarrow e\rho$	$2.3 \times 10^{-4}$	$2.4 \times 10^{-3}$
(121)(321)	$\tau \rightarrow e\rho$	$2.3 \times 10^{-4}$	$2.4 \times 10^{-3}$
(121)(322)	$\tau \rightarrow e\overline{K^{0*}}$	$2.9 \times 10^{-4}$	$3.6 \times 10^{-3}$
(122)(321)	$\tau \rightarrow eK^{0*}$	$2.8 \times 10^{-4}$	$2.9 \times 10^{-3}$
(122)(322) $\nu^{22}$	$\tau \rightarrow e\phi$	$2.3 \times 10^{-4}$	$3.4 \times 10^{-3}$
(131)(331)	$\tau \rightarrow e\rho$	$2.3 \times 10^{-4}$	$2.4 \times 10^{-3}$
(131)(332)	$\tau \rightarrow e\overline{K^{0*}}$	$2.9 \times 10^{-4}$	$3.6 \times 10^{-3}$
(132)(331)	$\tau \rightarrow eK^{0*}$	$2.8 \times 10^{-4}$	$2.9 \times 10^{-3}$
(132)(332)	$\tau \rightarrow e\phi$	$2.3 \times 10^{-4}$	$3.4 \times 10^{-3}$
(211)(311) $\nu^{11}$	$\tau \rightarrow \mu\rho$	$1.9 \times 10^{-4}$	$4.3 \times 10^{-3}$
(211)(312)	$\tau \rightarrow \mu K_S$	$3.8 \times 10^{-4}$	$2.4 \times 10^{-3}$
(212)(311)	$\tau \rightarrow \mu K^{0*}$	$3.8 \times 10^{-4}$	$3.6 \times 10^{-3}$
(212)(312)	$\tau \rightarrow \mu\rho$	$1.9 \times 10^{-4}$	$4.3 \times 10^{-3}$
(213)(313)	$\tau \rightarrow \mu\rho$	$1.9 \times 10^{-4}$	$4.3 \times 10^{-3}$
(221)(321)	$\tau \rightarrow \mu\rho$	$1.9 \times 10^{-4}$	$4.3 \times 10^{-3}$
(222)(321)	$\tau \rightarrow \mu K^{0*}$	$3.8 \times 10^{-4}$	$3.6 \times 10^{-3}$
(222)(322) $\nu^{22}$	$\tau \rightarrow \mu\phi$	$3.8 \times 10^{-4}$	$3.4 \times 10^{-3}$
(231)(331)	$\tau \rightarrow \mu\rho$	$1.9 \times 10^{-4}$	$4.3 \times 10^{-3}$
(231)(332)	$\tau \rightarrow \mu K_S$	$3.8 \times 10^{-4}$	$2.4 \times 10^{-3}$
(232)(331)	$\tau \rightarrow \mu K^{0*}$	$3.8 \times 10^{-4}$	$3.6 \times 10^{-3}$
(232)(332)	$\tau \rightarrow \mu\phi$	$3.8 \times 10^{-4}$	$3.4 \times 10^{-3}$

Table 4: Bounds on  $\lambda'_{ijk}\lambda'_{pqr}$  from  $\tau \rightarrow \ell + M$  decays, where  $M$  is a pseudoscalar or a vector meson. All squarks are assumed degenerate at 100 GeV. The superscript  $\nu ii$  indicates that the combination contributes to the  $ii$ -th element of the neutrino mass matrix.

$\lambda'\lambda'$	Upper bound	$\lambda'\lambda'$	Upper bound
(111)(311)	$4.1 \times 10^{-3}$	(211)(311)	$4.7 \times 10^{-3}$
(112)(312)	$4.1 \times 10^{-3}$	(212)(312)	$4.7 \times 10^{-3}$
(113)(313)	$4.1 \times 10^{-3}$	(213)(313)	$4.8 \times 10^{-3}$
(121)(321)	$4.1 \times 10^{-3}$	(221)(321)	$4.7 \times 10^{-3}$
(122)(322)	$4.1 \times 10^{-3}$	(222)(322)	$4.7 \times 10^{-3}$
(123)(323)	$4.1 \times 10^{-3}$	(223)(323)	$4.8 \times 10^{-3}$
(131)(331)	$7.8 \times 10^{-2}$	(231)(331)	$8.9 \times 10^{-2}$
(132)(332)	$7.8 \times 10^{-2}$	(232)(332)	$8.9 \times 10^{-2}$
(133)(333)	$10.4 \times 10^{-2}$	(233)(333)	$12.0 \times 10^{-2}$

Table 5: Bounds on  $\lambda'\lambda'$  type products from  $\tau \rightarrow e + \gamma$  (left) and  $\tau \rightarrow \mu + \gamma$  (right) decays.

## 4 Summary and conclusion

We have found limits on several product couplings of types  $\lambda\lambda$ ,  $\lambda\lambda'$ , and  $\lambda'\lambda'$  coming from lepton flavour violating  $\tau$  decays. These bounds should be marginally improved once the Belle collaboration finishes its data analysis. However, any super B factory will do a lot better, and these bounds can go up by orders of magnitude.

While some of these products do affect the neutrino masses and hence are possibly more tightly constrained than that discussed here, there are other low-energy processes that might be affected by these couplings. For example, the decay  $K \rightarrow \pi\nu\bar{\nu}$ , which is supposed to be a clean channel for the determination of the CP violating phase  $\sin(2\beta)$ , gets contribution from couplings like  $\lambda'_{i2k}\lambda'_{j1k}$  or  $\lambda'_{ik1}\lambda'_{jk2}$ .

Another interesting prospect is to find these LFV decays at the LHC. For the  $\lambda\lambda'_{i11}$  type couplings, one can observe a Drell-Yan type unlike-flavour dilepton production, mediated by a slepton propagator. The same applies for  $\lambda'\lambda'$  type couplings where the first generation quark fields come into play. These signals will be interesting to study.

### Acknowledgement

The author acknowledges the University Grants Commission, Government of India, for financial support. She also acknowledges helpful discussions with A. Kundu.

## References

- [1] R. Barbier *et al.*, Phys. Rept. **420**, 1 (2005) [arXiv:hep-ph/0406039].
- [2] M. Chaichian and K. Huitu, Phys. Lett. B **384**, 157 (1996) [arXiv:hep-ph/9603412]; A. de Gouvea, S. Lola and K. Tobe, Phys. Rev. D **63**, 035004 (2001) [arXiv:hep-ph/0008085]; J. Cao, L. Wu and J. M. Yang, Nucl. Phys. B **829**, 370 (2010) [arXiv:0908.4556 [hep-ph]].
- [3] J. P. Saha and A. Kundu, Phys. Rev. D **66**, 054021 (2002) [arXiv:hep-ph/0205046].
- [4] H. K. Dreiner, M. Kramer and B. O’Leary, Phys. Rev. D **75**, 114016 (2007) [arXiv:hep-ph/0612278].
- [5] B. C. Allanach, A. Dedes and H. K. Dreiner, Phys. Rev. D **60**, 075014 (1999) [arXiv:hep-ph/9906209].
- [6] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **104**, 021802 (2010) [arXiv:0908.2381 [hep-ex]]. Also see K. Hayasaka *et al.* [Belle Collaboration], Phys. Lett. B **666**, 16 (2008) [arXiv:0705.0650 [hep-ex]].
- [7] See the talk by K. Hayasaka, on behalf of Belle and BaBar Collaborations, at 22nd Rencontres de Blois, July 2010. Also see K. Hayasaka, for the Belle and BaBar collaborations, arXiv:1010.3746 [hep-ex], B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **98**, 061803 (2007) [arXiv:hep-ex/0610067], B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. D **79**, 012004 (2009) [arXiv:0812.3804 [hep-ex]].
- [8] See the talk by K. Hayasaka [Belle Collaboration], ICHEP 2010, Paris. Also see B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **103**, 021801 (2009) [arXiv:0904.0339 [hep-ex]].
- [9] K. Hayasaka *et al.*, Phys. Lett. B **687**, 139 (2010) [arXiv:1001.3221 [hep-ex]]. Also see J. P. Lees *et al.* [BaBar Collaboration], Phys. Rev. D **81**, 111101 (2010) [arXiv:1002.4550 [hep-ex]].
- [10] B. C. Allanach, A. Dedes and H. K. Dreiner, Phys. Rev. D **69**, 115002 (2004) [Erratum-ibid. D **72**, 079902 (2005)] [arXiv:hep-ph/0309196].